DOCUMENT RESUME

ED 255 390 SE 045 493

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TITLE Cognitive Restructuring as a First Step in Problem Solving.
PUB DATE 85
NOTE 10p.; Paper presented at the Annual Meeting of the National Association for Research in Science Teaching (58th, French Lick Springs, IN, April 15-18, 1985). For a related document, see SE 045 494.
PUB TYPE Reports - Research/Technical (143) -- Speeches/Conference Papers (150)

EDRS PRICE MF01/PC01 Plus Postage.
DESCRIPTORS *Chemistry; *Cognitive Structures; *College Science; *Heuristics; Higher Education; *Problem Solving; Science Education; *Spatial Ability
IDENTIFIERS *Science Education Research

ABSTRACT

Chemists have bemoaned for years their students' inability to solve problems in introductory chemistry courses. However, at least part of this inability must be attributed to the fact that chemists have historically tried to teach their students to solve problems by doing nothing more than working examples. In recent years, chemists have begun to realize the importance of general strategies or heuristics in problem-solving, and they have become particularly enthralled with the "road map" approach to problem-solving. There is abundant evidence, however, that students who understand this approach all too often still cannot solve "simple" stoichiometry problems. The hypothesis behind the research discussed in this paper is the assumption that there is a preliminary stage in problem-solving which most chemists have neglected. During this preliminary stage, relevant information is disembedded and the problem is restructured. Until this stage is successfully completed, students cannot proceed on to the analytic stage in which the road map heuristic can be applied. Preliminary evidence supporting this hypothesis is presented which suggests that there is a linear correlation between students' ability to handle disembedding and cognitive restructuring tasks in the spatial domain and their ability to solve "simple" stoichiometry problems. Nine references are listed. (Author/JN)

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COGNITIVE RESTRUCTURING

AS A FIRST STEP IN PROBLEM SOLVING

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1-317-494-5313

Paper presented at the National Association for Research in Science Teaching Meeting, French Lick Springs, IN, April, 1985

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SE 045 493

Abstract

Chemists have bemoaned for years their students' inability to solve problems in introductory chemistry courses. At least part of this inability must be attributed to the fact that chemists have historically tried to teach their students to solve problems by doing nothing more than working examples.

In recent years, chemists have begun to realize the importance of general strategies or heuristics in problem solving, and they have become particularly enthralled with the "road map" approach to problem solving. There is abundant evidence, however, that students who understand the road map approach to problem solving all too often still cannot solve "simple" stoichiometry problems, much less more complex problems in kinetics, electrochemistry, equilibrium, thermodynamics, etc.

The hypothesis behind the research discussed in this paper is the assumption that there is a preliminary stage in problem solving which most chemists have neglected. During this preliminary stage, relevant information is disembedded and the problem is restructured. Until this stage is successfully completed, the student cannot proceed on to the analytic stage in which the road map heuristic can be applied.

Preliminary evidence supporting this hypothesis will be presented which suggests that there is a linear correlation between the students' ability to handle disembedding and cognitive restructuring tasks in the spatial domain and their ability to solve "simple" stoichiometry problems.

Cognitive Restructuring as a First Step in Problem Solving

Only a small fraction of the students who take chemistry at either the high school or college level are volunteers. Most were drafted. They are there because they were told that a high-school chemistry course will help prepare them for college, or because someone made a college-level course a requirement for their major.

Why are so many students required to take chemistry? Perhaps because they need to be introduced to the language that chemists use to describe the world around us. A language that includes useful concepts such as solids, liquids, gases, acids, bases, metals, oxidation-reduction, electrochemistry, thermodynamics, kinetics, etc. More likely because of the style of problem solving chemists used to interpret experiments run on the macroscopic scale in terms of the structure of a sub-microscopic world we can never see. Perhaps one of the most important reasons why students are asked to take chemistry is to help them learn how to solve problems.

Problem solving is not just learning how to do gram-gram calculations or titration problems. It includes tasks such as predicting the products of the reaction of a metal with water, determining the formula of a carbonate by measuring the weight loss on heating, or deciding that polonium metal crystallizes in a simple cubic unit cell by measuring the density of the metal and the distance between planes of atoms in the crystal.

For the sake of argument, we will use John Hayes' definition of both problem,

> "Whenever there is a gap between where you are now and where you want to be, and you don't know how to find a way to cross that gap, you have a problem."

and problem solving. [Hayes, 1981]

"Solving a problem means finding an appropriate way to cross a gap."

These definitions provide us with a basis for distinguishing between problems and exercises. If you know what to do when you read a question, it isn't a problem, its an exercise. Thus, status as a problem is not a characteristic of an individual question, it is a subtle interaction between the question and the individual trying to answer the question.

The following question would be a problem for most students, but not for most chemists. [Greenbowe, 1983]

> A 2.395 g sample of an unknown chloride with the formula MCl_3 is dissolved in water and treated with excess silver nitrate solution. The mass of the AgCl precipitate formed is 5.168 g. What is the atomic weight of the unknown metal?

Many of us, particularly those who teach general chemistry regularly, know how to attack this question as soon as we see it. We can turn this question into a problem for virtually everyone, however, by pulling out some of the subtle hints that tell us how to attack the problem.

> A 2.395 g sample of an unknown chloride is dissolved in water and treated with an excess of a reagent that precipitates the Cl^- ion. The mass of the precipitate formed is 5.168 g. What is the atomic weight of the unknown metal?

A number of introductory texts in recent years have advocated a "road map" approach to problem solving. They suggest that basic gram-gram calculations, for example, can be done by constructing a map of the steps that have to be taken to get from grams of one reactant to grams of another.

g of reactant → moles of reactant → moles of product → g of product

We are willing to concede that these road maps are useful when solving exercises, but they are not sufficient for solving problems. Indeed, we might argue that if you can use a road map to find the answer to a question, you probably aren't solving a problem! Our favorite definition of problem solving was coined by Grayson Wheatley who suggested that problem solving is what you do when you don't know what to do. [Wheatley]

The work described in the first two papers today was based on the hypothesis that we have students in our classes who understand the road map for gram-gram calculations, and yet still cannot tell us how many grams of CO_2 are produced when 10.0 grams of glucose react with 10.0 grams of O_2. There is undoubtedly an analytic stage in problem solving in which a sequence of steps are taken in a more or less logical order. However, we argue that the more logical the order in which these steps are taken, the less likely that the process involves problem solving.

Furthermore, if we focus exclusively on the analytic stage in problem solving we are neglecting an important holistic or gestalt stage during which all of the elements of the problem are simultaneously juggled and the problem is reconstructed into a problem that has a more or less recognizable starting and ending point.

Almost 40 years ago, Polya suggested that there are four stages in solving a problem: (1) understanding the problem, (2) devising a plan, (3) carrying out the plan, and (4) looking back. [Polya, 1945] More recently, Hayes suggested six steps: (1) finding the problem (recognizing that a problem exists), (2) representing the problem (understanding the gap to be crossed), (3) planning the solution (choosing a method for crossing the gap, (4) carrying out the plan, (5) evaluating the solution (how good is the

result?), and (6) consolidating gains (learning from the experience of solving the problem). [Hayes, 1981]

Regardless of which problem solving model we use, there is a stage whose goal is understanding the problem, or finding the problem. A holistic or gestalt stage at which relevant information is disembedded from the problem, and the elements of the problem are juggled simultaneously until the problem is reconstructed or transformed into a new problem that the student understands (i.e., a problem for which the student recognizes the initial and goal states). Furthermore, we argue that unless students can get through this stage successfully, they can't solve the problem regardless of how well they understand the analytic processes involved in solving similar questions.

Chemistry teachers are so familiar with chemistry problems that they often forget what a challenge it is for beginning students to successfully complete this first stage of problem solving. We have therefore selected a few problems from a recent college text which demonstrate that a form of restructuring must take place before the problem can be solved. [Moeller, et al., 1984]

In the first example, there are a number of terms or symbols that have to be sorted before the student can tell whether they are important or not.

> "Find the standard state entropy of formation of HCl(g) at 25°C from the following absolute standard state entropies at 25°C: 186.80 J/K mol for HCl(g), 130.57 J/K mol for $H_2(g)$, and 222.96 J/K mol for $Cl_2(g)$."

In the second example, the student not only has to complete this task, (s)he also has to determine which of the three temperatures is (or are) important in this question.

"The standard heat of formation of $O_3(g)$ at 298 K is 142.7 kJ/mol and it varies negligibly with temperature up to 6000 K. Calculate the $\Delta G°$ of formation of ozone at 1000. K given that the $\Delta G°$ of formation is 163.1 kJ/mol at 298 K."

The third problem is the most obvious example of the phenomenon under discussion, the need to proceed through a holistic or gestalt stage in which relevent information is disembedded and the question is restructured before the student can begin to apply the analytic thought processes that eventually lead to an answer.

"A particular electrochemical cell consists of one half-cell in which a silver wire coated with AgCl(s) dips into a 1 M KCl solution and another half-cell in which a piece of platinum dips into a solution that is 0.1 M in $CrCl_3$, 0.001 M in $K_2Cr_2O_7$, and 1 M in HCl. In the cell described, the following reaction takes place:

$$Ag(s) + Cr_2O_7^{2-} + Cl^- + H^+ \rightarrow AgCl(s) + Cr^{3+} + H_2O(l)$$

The standard reduction potentials are 1.33 V and 0.22 V for the $Cr_2O_7^{2-}/Cr^{3+}$ and AgCl(s)/Ag, Cl^- couples, respectively. Write (a) the ion-electron equations for the half-reactions in this cell and the overall cell equation. Determine (b) the standard state potential and (c) the potential of the cell under the above non-standard conditions. (d) Calculate the equilibrium constant for the reaction."

What evidence do we have to support our hypothesis that there is an early holistic or gestalt stage in chemistry problem solving? In the last several years we have given a battery of spatial tests to students in the general chemistry sequence for engineering and science majors at Purdue.

Among the tests that we use are the Purdue Visualization of Rotations test [Guay and McDaniel, 1978] which examines the students' ability to handle cognitive restructuring tasks in the spatial domain, and the Find A Shape Puzzle [Linn and Kyllonen, 1981] which measures the students' ability to disembed relevant information in the spatial domain.

Preliminary results have shown a reasonable correlation between the students' performance on these spatial tests and their performance on general chemistry tests, including the final exam. [Bodner, et al., 1984; McMillen, 1983] Interestingly enough, the correlation between spatial ability and performance on multiple choice questions that focus on highly spatial tasks such as crystallography is no better than the correlation between spatial ability and performance on multiple choice questions that focus on "simple" stoichiometry problems.

These results suggest that there is indeed a holistic or gestalt stage in problem solving in which students must be able to disembed relevant information and restructure the problem, and furthermore, that students who are particularly good at the cognitive restructuring and disembedding required in this stage of problem solving may also excel at other tasks that require restructuring and disembedding.

The implications for teaching chemistry are obvious. It is quite possible that much of the effort now being expended at teaching problem solving in chemistry is misdirected because it focuses on a stage in problem solving that the students have already mastered in other courses, and does not focus on the stage in problem solving where students need the most assistance.

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